A Compact and Low-Power Two-Axis Scanning Laser Rangefinder for Mobile Robots

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Abstract

In this paper we present a prototype two-axis scanning laser rangefinder, or LIDAR, intended for use on small mobile robots. By combining a high speed, highly accurate single point laser range sensor with a custom high speed, compact scanning mechanism, we have developed a sensor which can provide remarkably high resolution images at a rate sufficient to support autonomous navigation and map buildings. The design is simple and elegant using only two actuators and a single mirror arranged in a gyroscope-style layout. The resulting system is lighter, smaller, and consumes less power than comparable commercially available systems. The prototype has a perceptual range of 360 continuous degrees HFOV, −10 to +15 degrees VFOV, and 0 to 10m with a variance of less than 1mm. Power consumption is less than 10W in full-scan mode, and the scanner occupies a volume of less than 3,100 cm^3. These features make it attractive for use in mobile robot systems where both power and space are at a premium.

1 Introduction

"Urbie" was developed as part of the Tactical Mobile Robots program which is funded by the Defense Advanced Research Project Agency. The goal of the program is to develop small, rugged mobile robots capable of autonomous or tele-operated urban reconnaissance. Unmanned reconnaissance robots may reduce the danger posed to response teams of urban crises such as disaster response or hostage situations by providing imagery or maps before personnel are deployed. At the end of 1999, the autonomous capabilities of Urbie included stereo vision-based obstacle avoidance at up to 80 cm/sec, visual servoing to user-designated goals, and vision-guided stair climbing. In future work, the objectives are to extend these capabilities to nighttime operations and to add indoor mapping. [1]

The overall weight and size of Urbie are driven by the program requirement that the robot be carried and deployed by one person. Urbie weighs approximately 20kg and is 60cm long. The complexion of the payload is limited by the number of sensors that will fit on the chassis along with the batteries and processors.

Vision, particularly stereo vision, is a common sensing modality for mobile robots. However, robots in the Tactical Mobile Robot program are tasked to operate in a wide variety of environments including lighting conditions such as direct sunlight, shadows, dark, or smoke. These conditions make vision difficult or impossible. Since perception is a cornerstone for autonomous systems, enabling a reliable high-speed sensing modality to

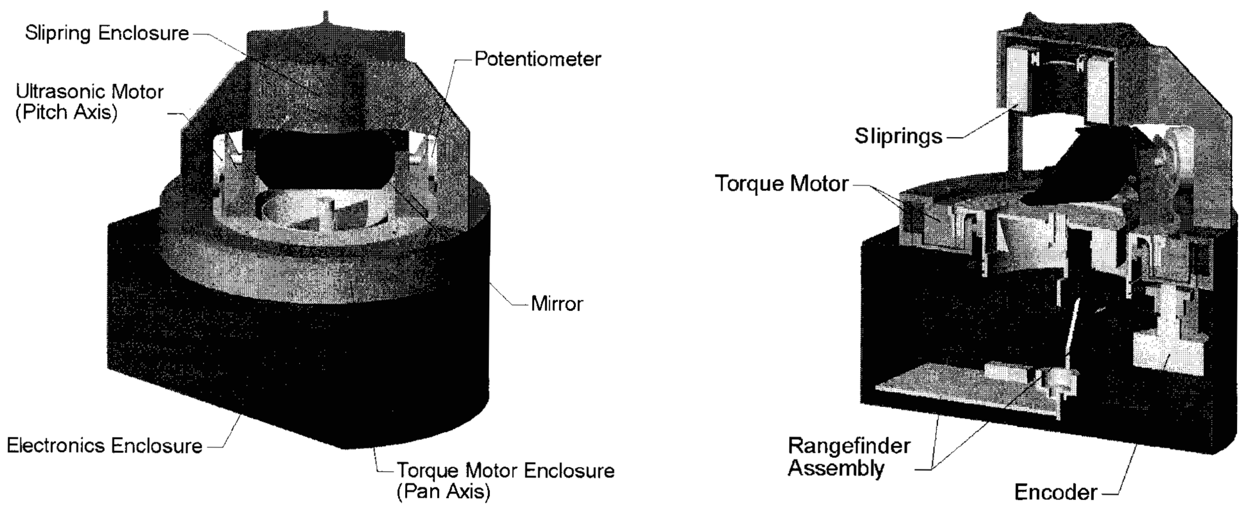

Figure 1 Two-axis laser scanner. (a) Prototype model (b) CAD model cross-section

complement vision for navigation and mapping is a key challenge. Scanning laser rangefinders (or scanners) are well suited to operate in these conditions, as they are active rather than passive like vision. Combined together scanners and vision form a complimentary, redundant perception system.

While a good deal of work has been done with the goal of equipping robots with laser rangefinders, the vast majority has been focused on larger vehicles or employed scanners too large to be practical for robots the size of Urbie. Some highlights of prior research includes detecting navigational hazards on Nomad[2], terrain mapping on DanteII[3], and path generation and following with Pioneer robots. [4] Most commercial scanners were developed for industrial applications and are bulky and power hungry. This work focuses on developing a compact, low weight, low power scanner that achieves the accuracy and range of its commercial brethren.

Section 2 summarizes the design goals and constraints for the laser scanner. A system overview of the prototype scanner is present in section 3. Preliminary performance data is presented in section 4. Section 5 summarizes the contributions of this work and key areas for future work.

2 System Requirements

2.1 Design Constraints and Objectives

The first two constraints are size and power: the scanner must fit within the space and power budgets afforded by the chassis. Since Urbie is autonomous, all perception, computation, and power resources are carried on board the robot. The mobility chassis is an Urban II tracked platform developed at IS Robotics. The chassis is approximately 60cm long, 50cm wide, and 17cm tall with roughly 13,000 cm^3 of payload space. A 20-cell NiCad battery pack provides a total power budget of 100Wh. Power consumption with the robot standing still is approximately 75W, and the power required for driving varies with the terrain. The robot and all subsystems must be able to survive the shock of being thrown or dropped modest distances.

The scanner will have three main functions – detect navigational obstacles, map indoor areas, and estimate robot position indoors by estimating the scan-to-scan motion. To map indoor areas efficiently from a mission perspective, the robot should have the flexibility to incrementally build up maps as it is moving or map a large area at once while the robot is stopped. For this task, the scanner must have a reasonably useful range and have a horizontal field of view (HFOV or pan) of 360 degrees. Continuous pan would be advantageous.

Autonomous navigation at higher speeds requires further look ahead. How far to look ahead is a function of the reaction time of the robot and of the speed at which the robot is moving. Given a constant reaction time, a slower speed will require less look ahead than faster speeds. This implies the need for a scanner with a maximum range to match the maximum speed of the robot and the ability to change the angle at which the laser intersects the ground plane (VFOV or tilt). Furthermore, indoor mapping would be enhanced by a variable tilt angle – allowing more detailed floor models to be constructed.

High-speed navigation drives the requirements for resolution. The pixel size and spacing must be fine enough to detect a nontraversable obstacle at distances great enough so that the path planner can navigate around it instead of simply reacting to it. This also drives the resolution of the beam positioning sensors and the size of the field of view. Computing capacity must also be considered as the amount of data increases.

Requiring the laser range sensor to be eye safe is a practical concern. However, since lower power levels degrade sensor range and accuracy characteristics, it is important not to overly limit the laser power level.

Manufacturer	Units	**Acuity**	**Sick**	**Riegl**	**Riegl**	**Cyra**
Model	-	AR4000-LIR	LMS-200-30106	LMS-Z210	LMS-Q140i-80	Cyrax 2400
Mass	kg	1.6	4.5	13	6	29.6
Volume	cm^3	2,600	4,500	15,000	14,800	63,300
Power	W	23.5	17.5	54	30	125
HFOV	degrees	+/- 150	+/- 180	+/- 170	+/-40	+/-20
VFOV	degrees	-	-	+/-40	-	+/-20
Spacing	degrees	0.18	0.5	0.24	0.14	0.04
Divergence	mRad	0.5	5	3	3	0.06
Horizontal scan rate	Hz	45	40	10	10	2
Sample frequency	-	100 - 50,000		5500	5500	
Range	m	0 to 15	2 to 150	0 to 8	0 to 8	0.5 to 50
Deviation (1 sigma)	mm	0.5	5	15	15	6
Laser safety class	-	IIIb	I	I	I	II
Ranging method		Time of flight	Time of flight	Time of flight	Time of flight	Time of flight
Mechanism		Rotating mirror	Polygonal Mirror	Rotating Sensor	Polygonal Mirror	Dual Mirror

Table 1 Comparison of commercially available scanning laser rangefinders.

When the specifics for Urbie were considered, the following list of design objectives emerged:

- Smallest possible footprint
- Lowest possible power consumption
- 0 to 10m range with centimeter accuracy
- 2 DOF: 360° HFOV; -15°/+30° VFOV
- Programmable pixel spacing up to 50mm at 10m
- Horizontal scan speed no less than 10Hz
- Full frame scan in 10 seconds
- Variable sampling frequency
- Class I Laser Safety

2.2 Commercially Available Scanners

Table 1 lists the commercially available scanning laser rangefinders that were considered. The predominant ranging method is pulse time-of-flight. A laser beam pulse is emitted and reflected off an object. The scanner's receiver detects the reflected light energy, and the time between transmission and reception is measured and converted to distance.

No one commercially available scanner met all the design criteria listed in the previous section.

3 Developed Scanner

It was decided to design and build a custom scanning laser rangefinder to meet the previously outlined requirements of the Tactical Mobile Robot program. The result is system comprised of a two-axis scanning mechanism developed at JPL and rangefinding optics developed by Acuity Research.

As shown in Figure 1, the scanner is arranged similar to a gyroscope with a pan motor to continuously rotate the tilt axis. The optical axis of the laser range sensor and the rotation axis of the pan motor are collinear. With this configuration only one mirror is needed to generate 3D images.

Two modes of operation are possible – fixed tilt-angle scans (2D) or full-scan mode (3D). Commanding the mirror to a fixed tilt angle produces a radial scan that is useful for high-speed applications such as obstacle detection, map building, and position estimation. By stepping the tilt angle after each full rotation of the pan axis, a 3D scan is produced which is useful for slower-speed applications such as 3D mapping and landmark recognition.

3.1 Laser Range Sensor

The AccuRange 4000 from Acuity Research was selected as the laser range sensor. It provides highly accurate and repeatable range readings at sampling rates which could meet the needs of autonomous navigation. Acuity's rangefinding technique is based on a patented modulated beam transmission and detection technique that differs from conventional pulse time-of-flight. The times to be measured are extremely short, and the electronic circuits measuring this time suffer from thermal drift thus degrading range accuracy and repeatability. Acuity addresses this problem by measuring frequency based on several periods instead of the direct travel time of the beam. Modulating the emitted laser with the signal from the collected return light forms a local oscillator, and it is the frequency of this modulation that is measured. A calibration look-up table maps a measurement triplet of frequency, intensity, and sensor temperature into a range reading. [5]

The sampling rate is programmable up to 50 kHz, and two operating powers – 3mW and 20mW – are user selectable. The AccuRange 4000 was reduced to the smallest possible footprint. Modifications included reducing the Fresnel lens of the collection aperture from 3 to 2 inches in diameter, reducing the focal length to 2 inches, and changing the form factor of the electronics from a single 3x6 inch board to two 3x3 inch boards which mount in an "L" configuration. The modified optics are shown in Figure 1b. These modifications reduced the guaranteed range from 15m to 10m but did not affect accuracy or repeatability.

3.2 Scanning Mechanism

The laser range sensor is mounted within a scanning mechanism developed at JPL. The prototype unit is 130mm wide, 160mm long, 150mm tall – occupying approximately 3120cm^3. There are two degrees of freedom – continuous 360 degree rotation on the pan axis and limited rotation on the tilt axis. The design incorporates a brush-commutated, frameless, thru-shaft DC motor for the pan axis and an ultrasonic motor for actuation on the tilt axis. An ultrasonic motor was chosen for the tilt axis. Besides being very compact, an ultrasonic motor has the advantage of being self-braking so that when power is removed the rotor and stator lock together. This feature is key in reducing power and control effort needed to maintain a desired tilt angle. A miniature DC motor with a brake would be at least a factor of 3 larger. A 3:1 miniature planetary gearhead is mounted between the ultrasonic motor and the mirror. A similar gearhead is mounted between the mirror and the linear potentiometer that is used to sense tilt angle. The thru-shaft motor was chosen to allow the optical axis of the laser range sensor to be collinear with the axis of rotation of the pan axis.

A single, flat, first-surface mirror is mounted collinear with the tilt axis and perpendicular to the optical axis. This simple design reduces the pointing function to the familiar polar to cartesian transformation. Typical scanning mechanisms use free-spinning polygonal mirrors and sense the mirror angle at each sample. The flat mirror used here consumes less space, but the mirror angle must be closed-loop controlled.

3.3 Control

The High Speed Interface (HSIF) from Acuity is an interface board resident on Urbie's navigation CPU and serves as a communication bus and buffer for samples from the AccuRange 4000. Samples are in an 8-byte format that includes a 19-bit range value and 1-byte values for amplitude, ambient light, sensor temperature as well as encoder and index pulse data for the pan motor. The complete data structure is collected each sampling period which allows for precise synchronization between the range data, position data, and other external events. The HSIF buffer holds 2,000 samples and stops sampling when the buffer is full to prevent data corruption. The HSIF also includes a variable voltage control for two DC motors.

Eight digital outputs and four digital inputs on Urbie's navigational CPU are used to control the ultrasonic motor, power management for the scanner components, and other scanner functions. The speed of the ultrasonic motor is set with a trimmer potentiometer, only the direction needs to be commanded.

A 512-line two phase quadrature encoder is coupled to the pan axis with a 4:1 gear ratio giving 2048 lines per revolution. A further factor of four is gained in the resolution since the HSIF measures each phase change from the quadrature encoder. This results in an angular resolution of 0.044 degrees for the pan axis. A photo-interrupter generates an index pulse at the zero pan angle.

By the law of reflection, when the mirror moves 1 mechanical degree, the laser beam moves 2 degrees. So a mirror angle of 45 mechanical degrees on the tilt axis would correspond to 90 optical degrees. When this is combined with the 3:1 planetary gear, a virtual 3:2 gear ratio is seen by a 1% linear, single-turn potentiometer thus increasing the tilt angle resolution. To reduce system components, the 8-bit analog to digital converter (ADC) used for converting sensor temperature on the HSIF was multiplexed so the tilt angle could be sensed as well. A hard stop provides a calibration point for the tilt mirror but is outside the region of interest of normal operation. In order not to sacrifice resolution or risk saturating the ADC, a two-mode amplifier was used to allow course position sensing over the entire range of motion of the mirror and fine position sensing over the normal operational range of the mirror. Since one bit of the ADC is dropped for noise suppression, a tilt resolution of 0.30 mechanical degrees (0.60 optical degrees) is realized in fine positioning mode. The gain to the instrumentation amplifier is selectable through an analog switch and controlled by a digital output on the Urbie's navigation CPU.

VxWorks serves as the real-time operating system for Urbie. All scanner control algorithms and the mapping from sensor data to range data are executed in software.

4 Preliminary Performance

A prototype was constructed and has used for characterizing the system capabilities. Currently, imaging is only being done in line-scan mode while control and sensing are being improved for the tilt axis. Table 2 lists the properties of the prototype scanner.

Parameter	Units	
Mass	kg	2.2
Volume	cm^3	3,100
Power	W	9.2
HFOV	degrees	360 continuous
VFOV	degrees	-10 to +15
Horizonal Spacing	degrees	0.044
Vertical Spacing	degrees	0.6
Divergence	mRad	0.5
Horizontal scan rate	Hz	10
Vertical scan rate	deg/sec	1,500
Sample frequency	Hz	100 to 50k
Range	m	0 to 10
Deviation (1 sigma)	mm	1
Laser safety class	-	IIIb
Ranging method		Time of flight

Table 2 Properties of the prototype scanner.

4.1 Power Consumption

The ultrasonic motor driver requires a 24VDC supply. 24VDC power is supplied to the motor driver side of the HSIF for the pan motor. A pan motor speed is commanded by selected a voltage level from the variable voltage output on the HSIF. The laser range sensor, the sensing electronics, and the peripheral electronics run on 5VDC. All power is relay-switched so that components may be shut off when not needed thereby conserving power.

Power draw was measured by connecting a watt meter in-line between the power supply and the scanner. The average power for each component was measured separately. Then the power consumption for the line-scan mode was measured. The results are shown in Table 3.

Component	Power (W)
Ultrasonic Motor	16.8
Pan Motor	4.2
Laser Range Sensor	2.4
Worst Case (All components)	23.4
Observed Average	7.2

Table 3 Power consumption of prototype scanner in line scan mode.

In line scan mode, 20ms is required to move the tilt mirror to the desired angle. Once the desired angle is achieved, the power relay to the ultrasonic motor is opened. Then a complete 360-degree scan is made on the pan axis.

The worst case power consumption is 23.4W if all components were running. From these results the power consumption for the full-scan mode can be reasonably estimated by adding the power consumed by the ultrasonic motor. In full-scan mode, 2 complete 360-degree scans are taken at 2-degree increments from −10 to +14 degrees on the tilt axis. The ultrasonic motor will have a duty cycle of approximately 12% consuming 2W or 9W total power for full-scan mode.

4.2 Range Performance

In order to characterize the range performance of the scanner the laser beam was set to a fixed position by disconnecting the pan motor and the tilt motor. First, moving a cardboard target from 50mm to a distance of 10m tested range accuracy and deviation. The target was at normal incidence, and 1,000 samples were collected at each distance. The results are shown in Figure 2. There was a constant offset of 76mm between the actual and perceived difference, and standard deviation was less than 1mm for all distances. At 10m, the scanner still receives sufficient return energy to make a good measurement. Unfortunately the laser test area was only 10m, so longer distance tests were not possible.

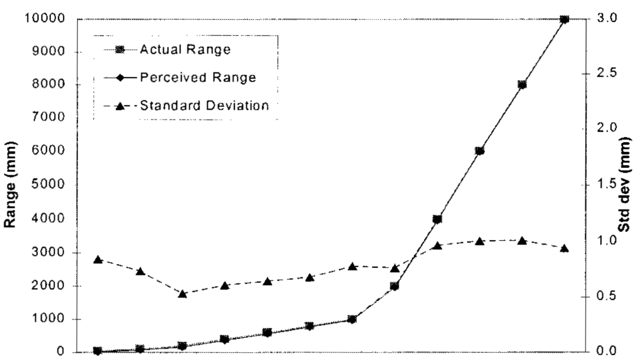

Figure 2 Range accuracy and deviation over various distances.

Next the same cardboard target was placed at approximately 3m, and the incidence angle between the target and the beam was increased from 0 to 89 degrees. 1,000 samples were taken at each angle. The results are shown in Figure 3 which shows the 76mm offset clearly. The range accuracy and standard deviation are unaffected by the angle of incidence until 70 degrees after which the data is unreliable.

4.3 Line-Scan Mode

Setting the tilt axis to a fixed angle and rotating the pan motor through one revolution produces line scan images of the surrounding scene. In our application, line scans will be used primarily for detecting navigation hazards and map building. Figure 4 shows how successive line scans can be registered and built up into a map. Figure 4a through Figure 4c show line scans from the beginning, middle, and end of the path respectively. Figure 4d shows the map produced with scan matching algorithms developed by Thrun. [6] The larger room is approximately 5m by 6m. The passage near point B is 2m wide.

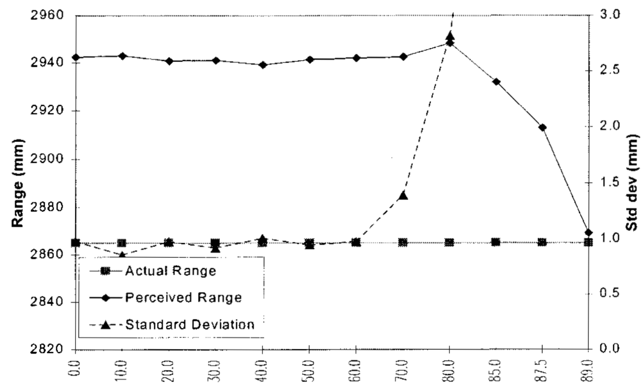

Figure 3 Range accuracy and deviation over various angles of incidence.

5 Conclusions and Future Work

By making the most critical element, the laser range sensor, as small as possible, we were able to build a precision scanning mechanism around it which meets the space and power payload requirements posed by the Tactical Mobile Robot project. The result is a high speed, compact, rugged two-axis scanner that is capable of supporting a variety of roles including hazard detection and indoor mapping.

Completing work on the full-scan mode is the last step to completing the prototype. Increasing the resolution of the tilt axis position sensor and reducing power consumption are high priority items. Currently, the laser is occluded at downlook angles greater than 10 degrees by the pan motor. Reducing the diameter of the pan motor will alleviate this and reduce the footprint of the scanner. Improving the packaging in other areas will reduce the scanner footprint as well. Before the scanner be fielded on an outdoor, a protective cover will need to be added to the system. Eye safety is also a concern that must be addressed if the scanner is to be used in populated areas.

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Acknowledgements

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Defense Advanced Research Projects Agency through an agreement with the National Aeronautics and Space Administration.

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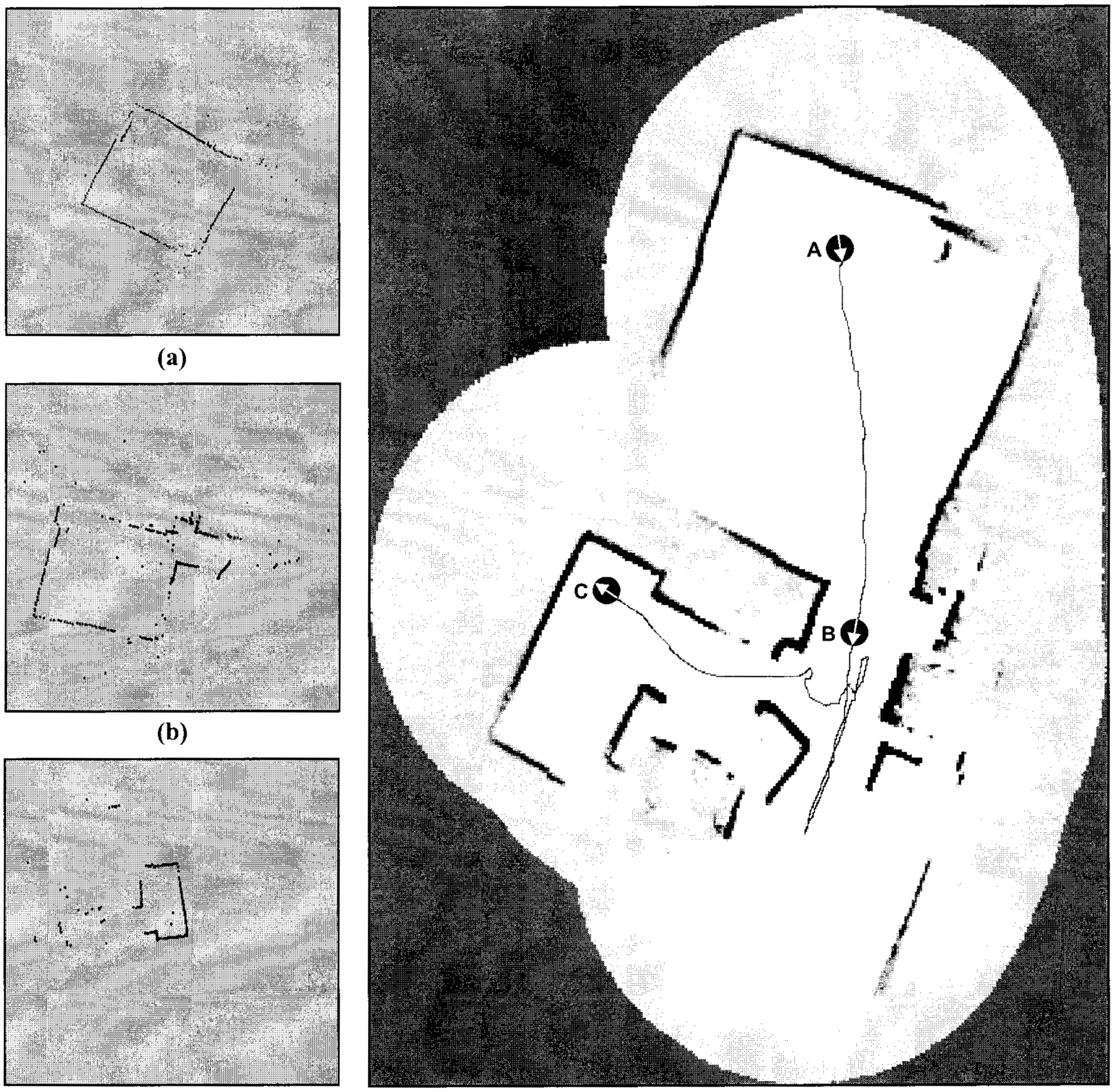

(a) **(b)** **(c)** **(d)**

Figure 4 Indoor Mapping. (a)-(c) Single line scans. (d) Map built from line scan.